

# Cryogenic detectors and neutrino mass measurement

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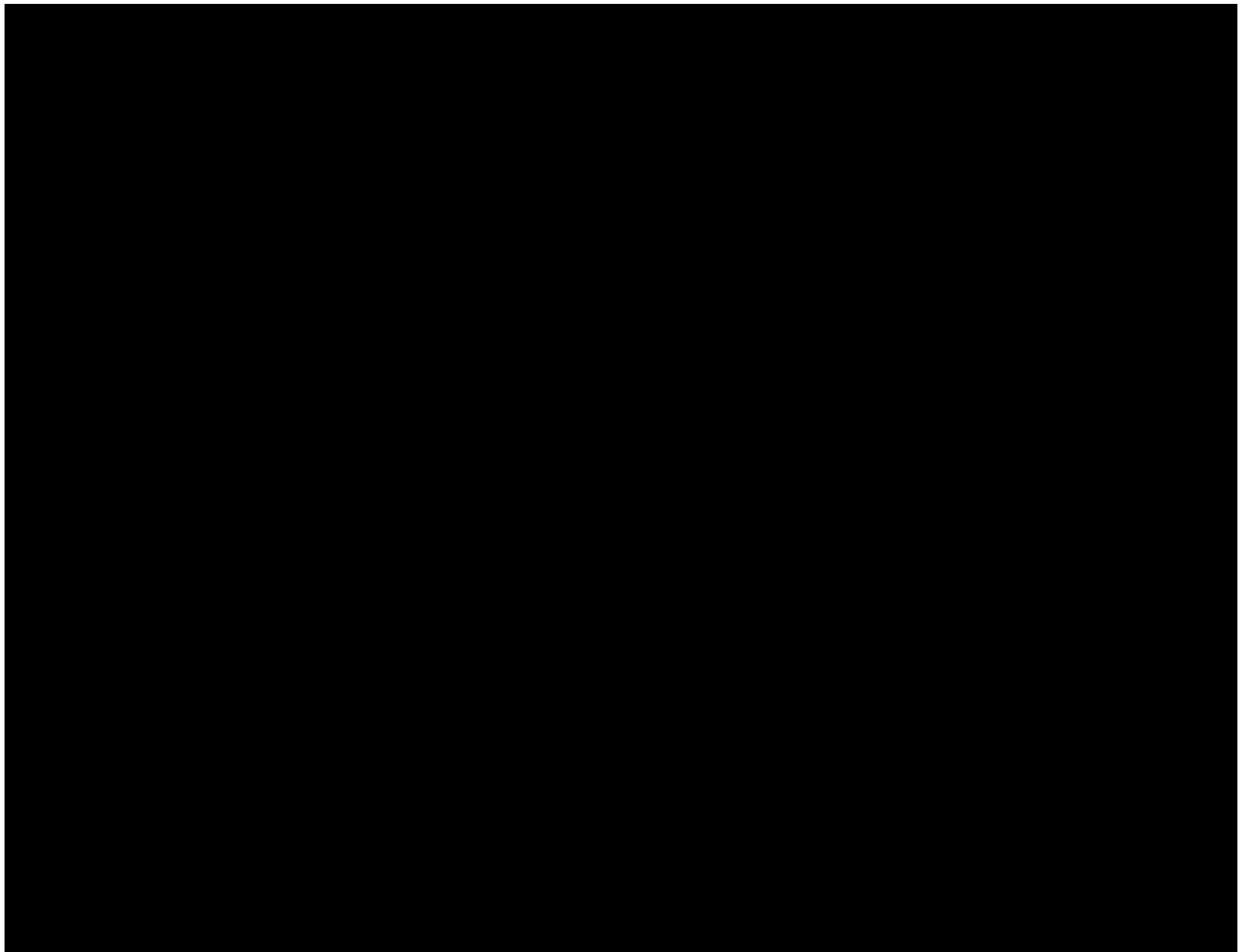
<sup>3</sup>Western Michigan University, Kalamazoo, MI, USA

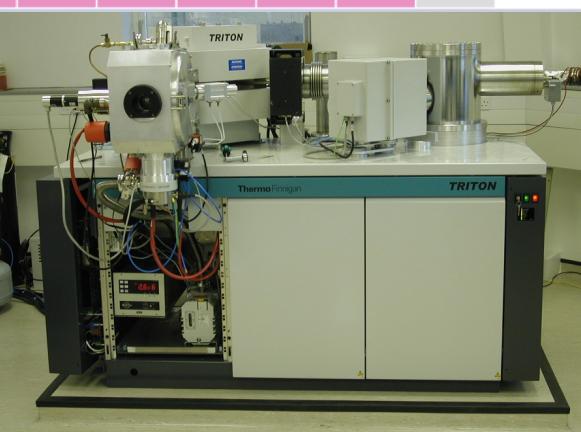
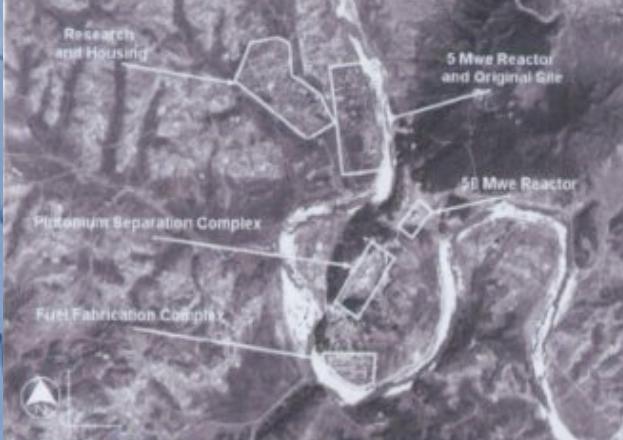
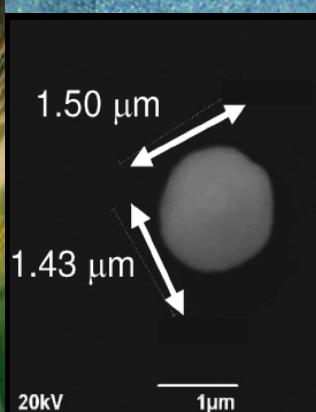
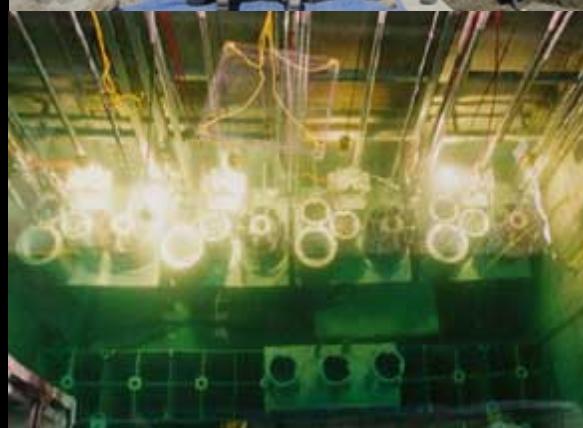
<sup>4</sup>University of Colorado, Boulder, CO, USA

<sup>5</sup>Star Cryoelectronics, Santa Fe, NM, USA



26 July 2013

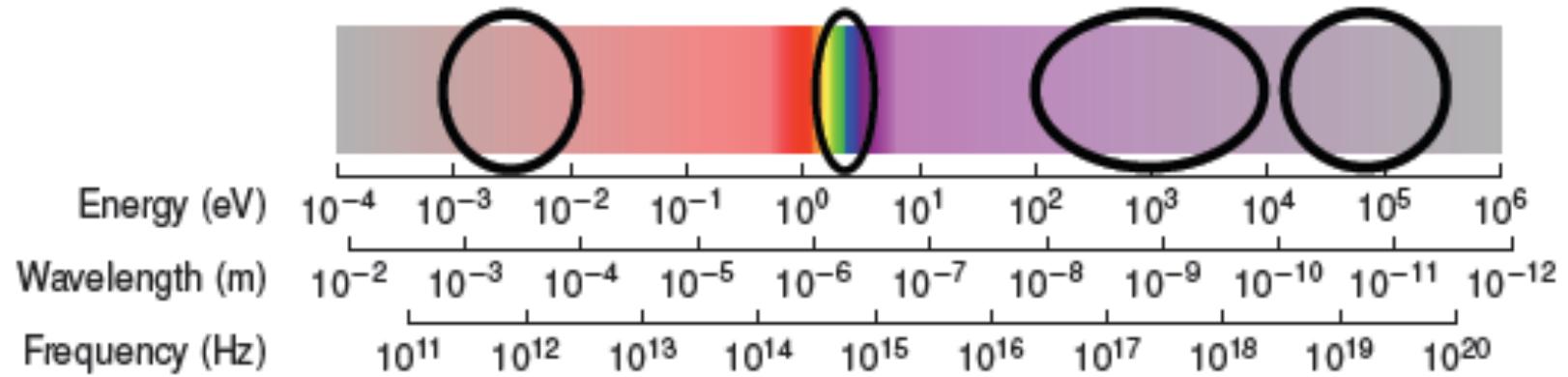




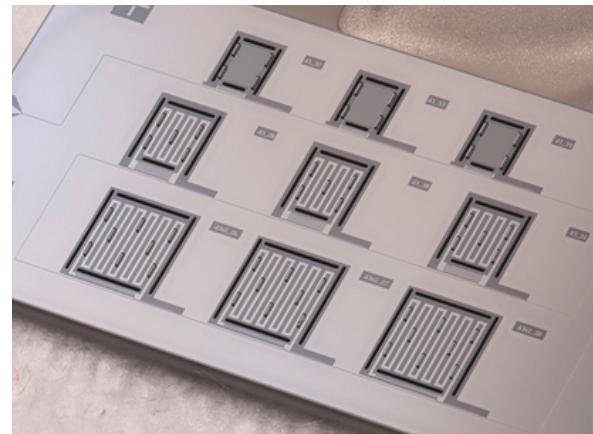
# Key science ideas for low temperature detectors

- Very low temperatures for low noise, now much more easily achieved  
*10 mK < T < 10 K with no liquid He and no liquid N<sub>2</sub>*
- Superconductors allow us to do things **impossible** with conventional materials  
*Very low band gap (meV) compared to semiconductors or scintillators (eV)*
- Exploit low noise for unparalleled measurement performance (SNR)  
*Magnetic or electric field, power, energy, time*
- Use for quantitative nuclear materials characterization  
*X-ray, gamma-ray, alpha particle, nuclear reaction energy spectroscopy*
- Apply to nuclear forensics, treaty verification, and international safeguards  
*Areas where we should strive to be a world leader*

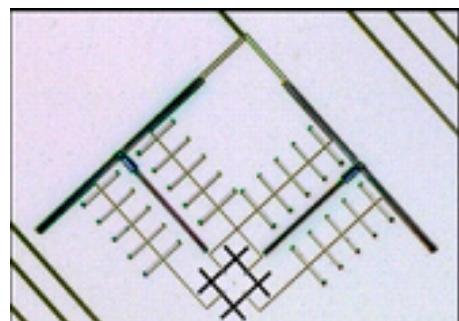
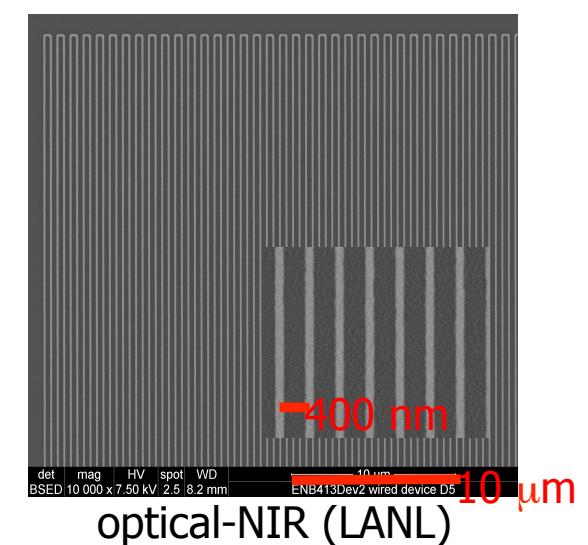
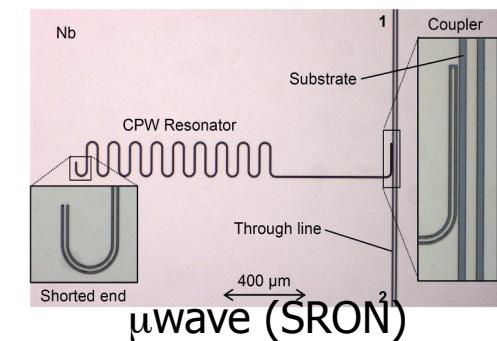
# Applications of low-temperature detectors



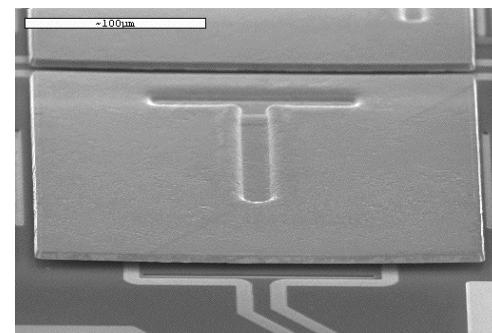
dark matter (Stanford)



gamma KIDs (LANL + NIST)



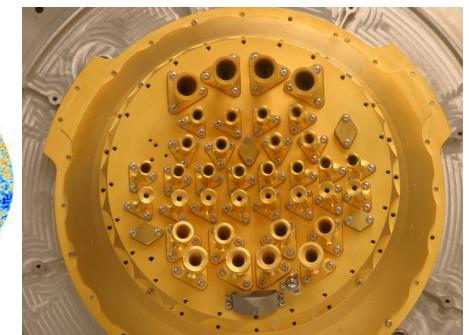
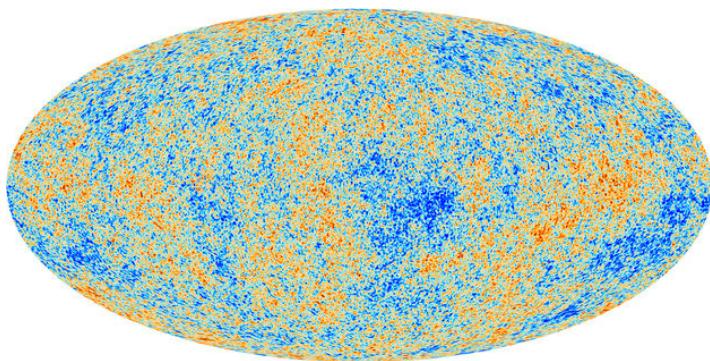
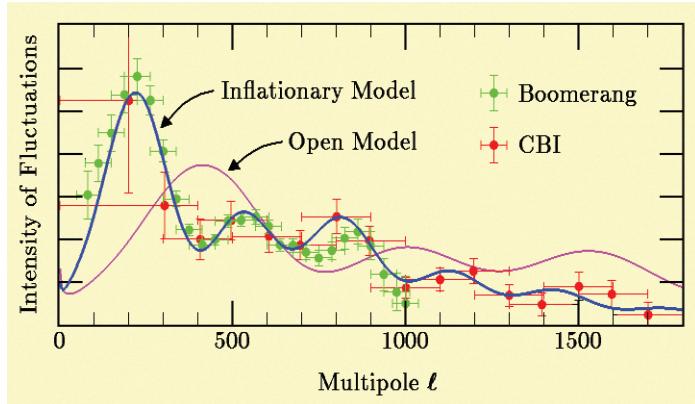
mm-wave (UCB)



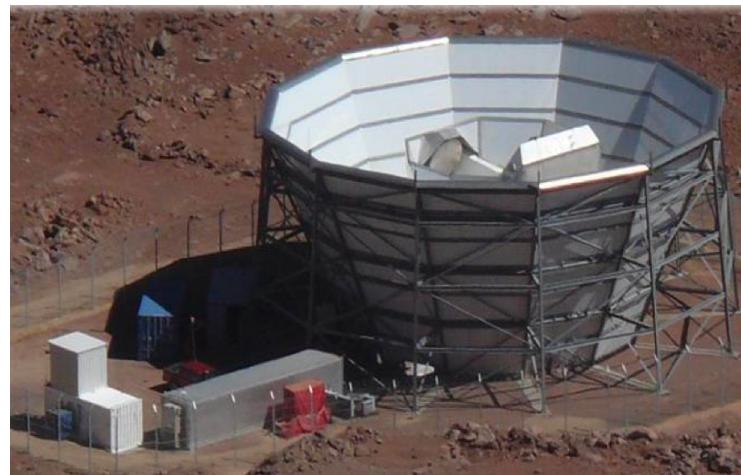
soft X-rays (NASA)

# Precision cosmology

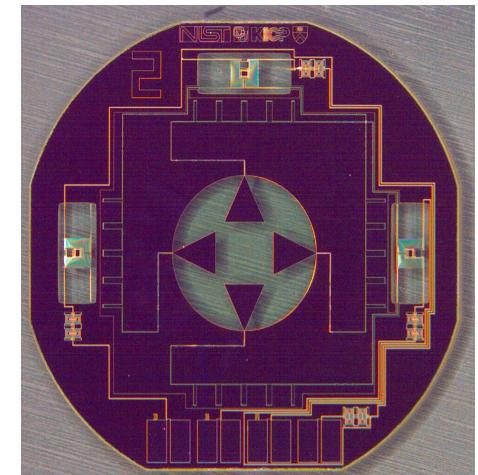
*The age of the universe is  $13.798 \pm 0.037$  billion years.*



South Pole Telescope  
~ 1,000 TES pixels



Atacama Cosmology Telescope  
~ 3,000 TES pixels



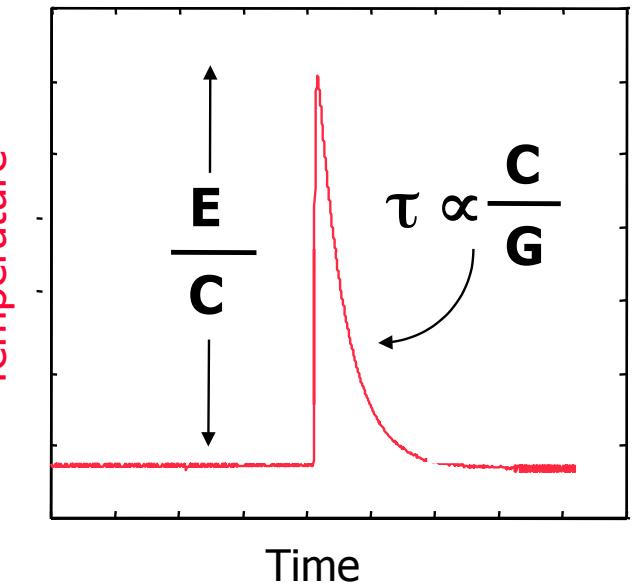
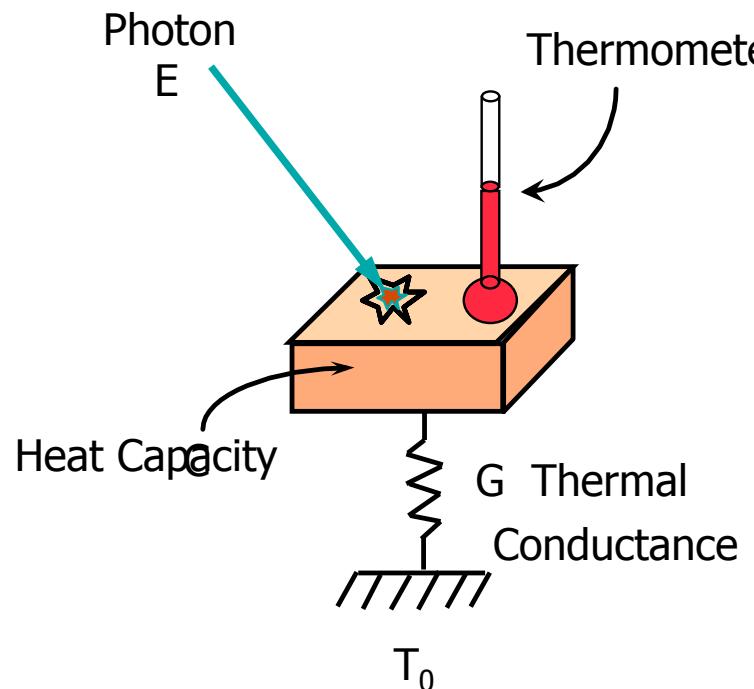
B-mode search  
polarimeter pixel

# Thermal sensors – bolometers and calorimeters

*Measure temperature to determine absorbed power or energy*

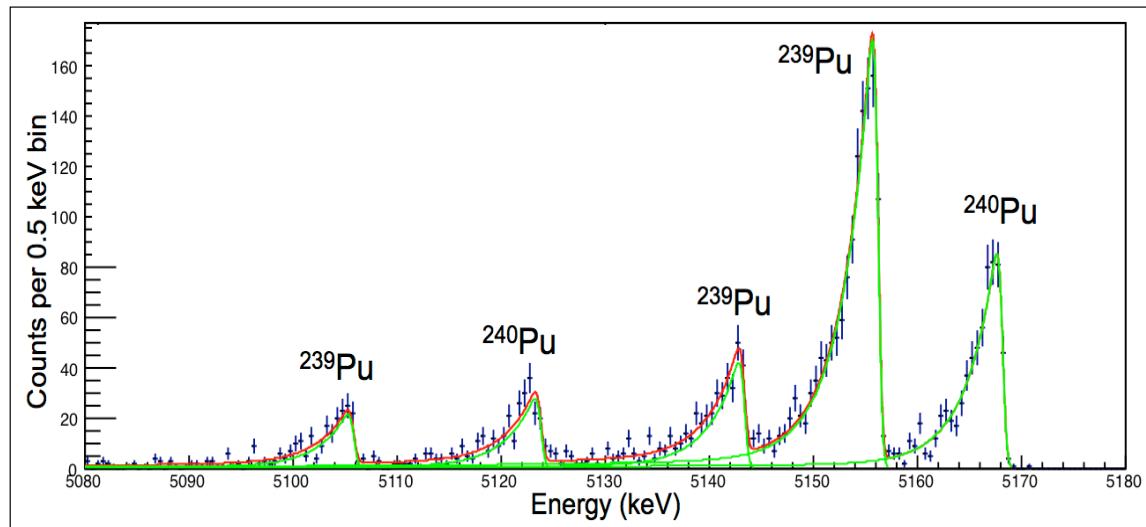
Many possible thermometers:

- neutron transmutation doped germanium
- implanted silicon
- dilute diamagnetic alloys
- magnetic penetration depth
- superconducting transition-edge (TES) sensors



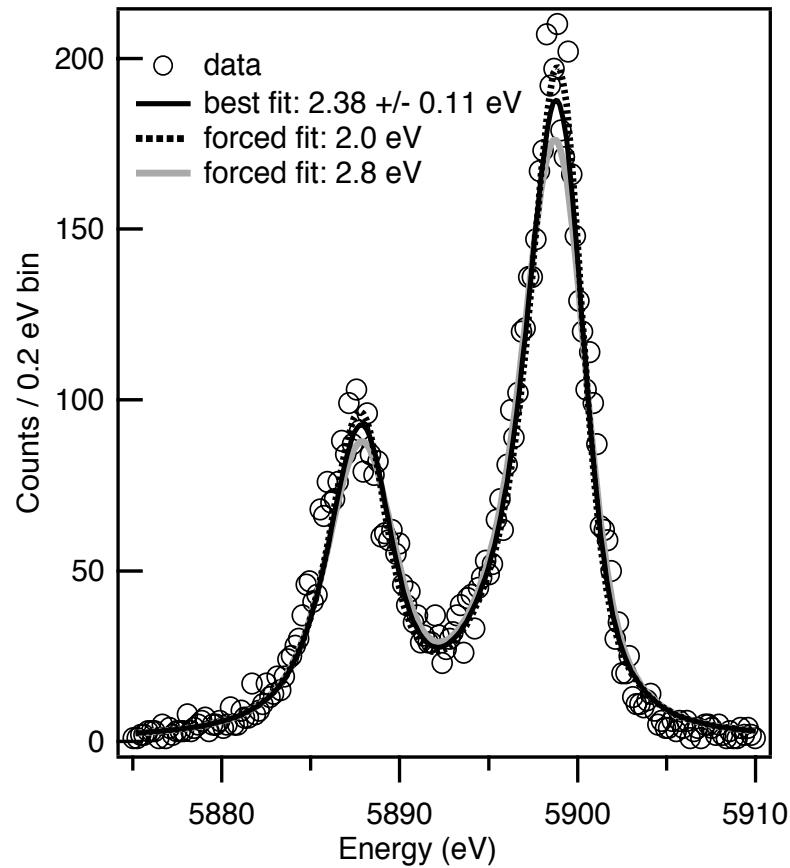
$$\Delta E_{FWHM} = 2.35 \sqrt{\frac{4k_b T^2 C}{\alpha}} \sqrt{\frac{n(1+M^2)}{2}}$$

Radiation Measured	Energy Range	Energy Resolution
X-ray	5 - 6 keV	1.6 - 2.5 keV
X-ray/Gamma	100 keV	22 eV
Alpha	5.0 MeV	0.8 keV
Q	6.0 MeV	2.3 keV



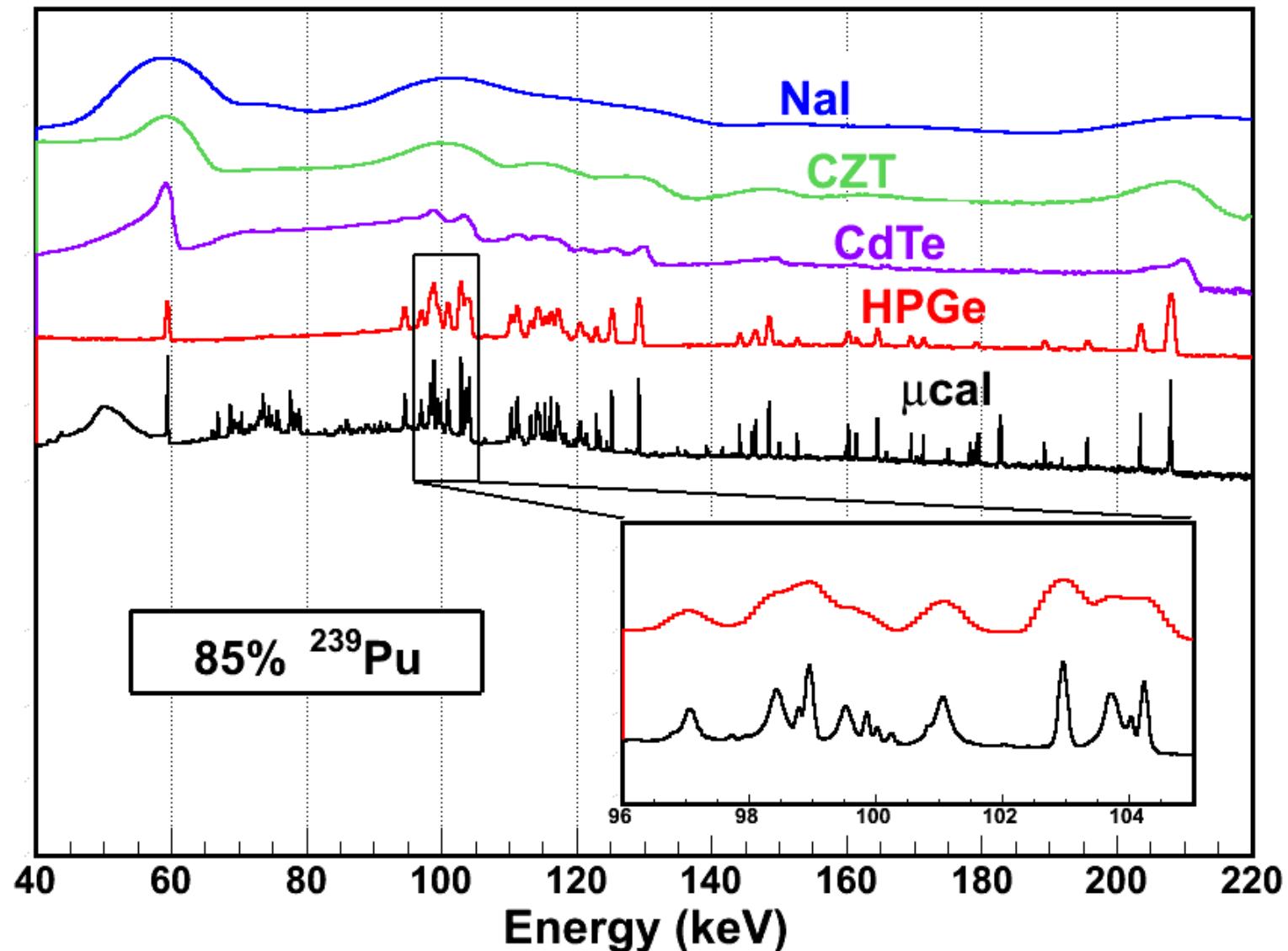
# Energy resolution for X-ray spectrometry

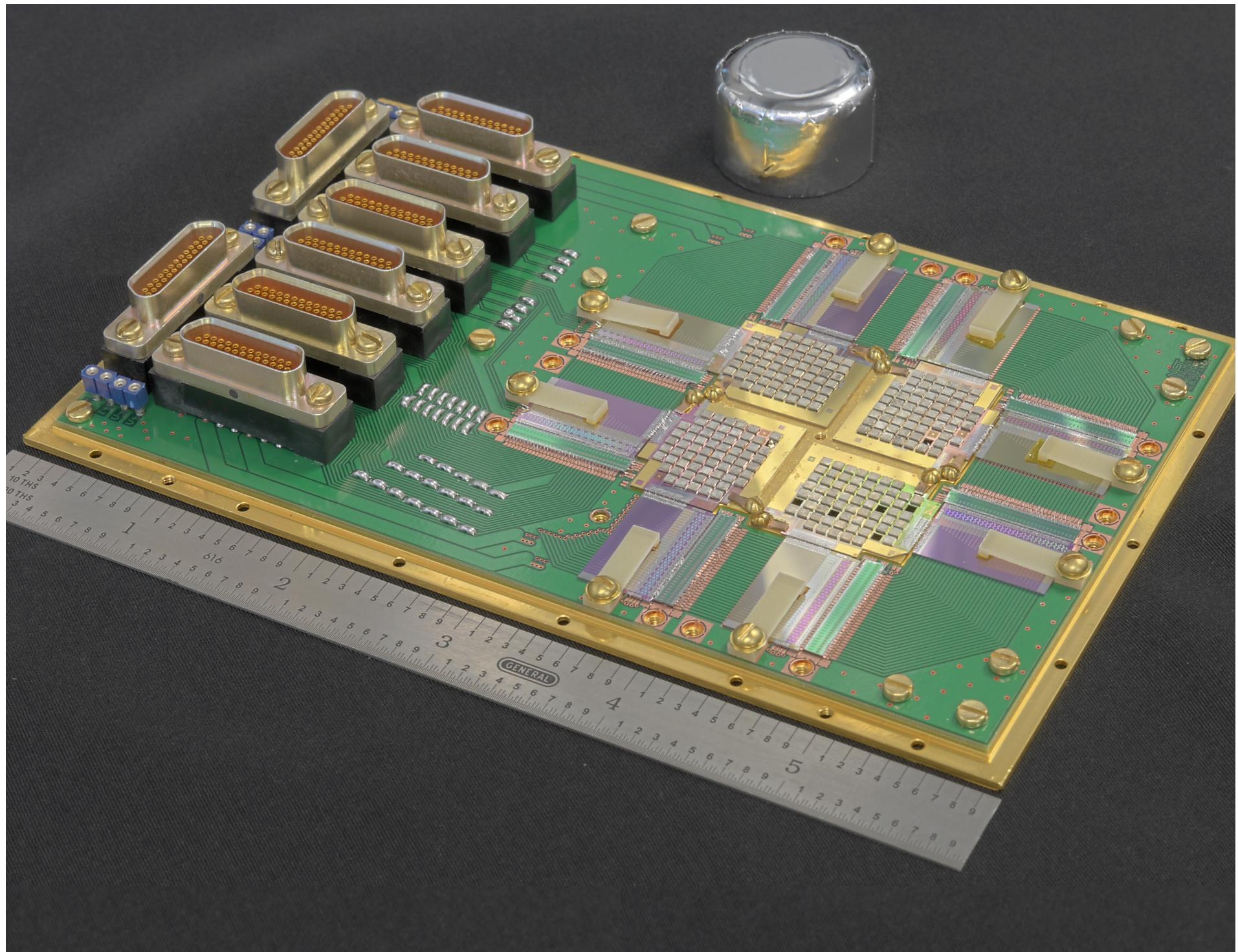
*Factor of ten better than conventional semiconductor technology*

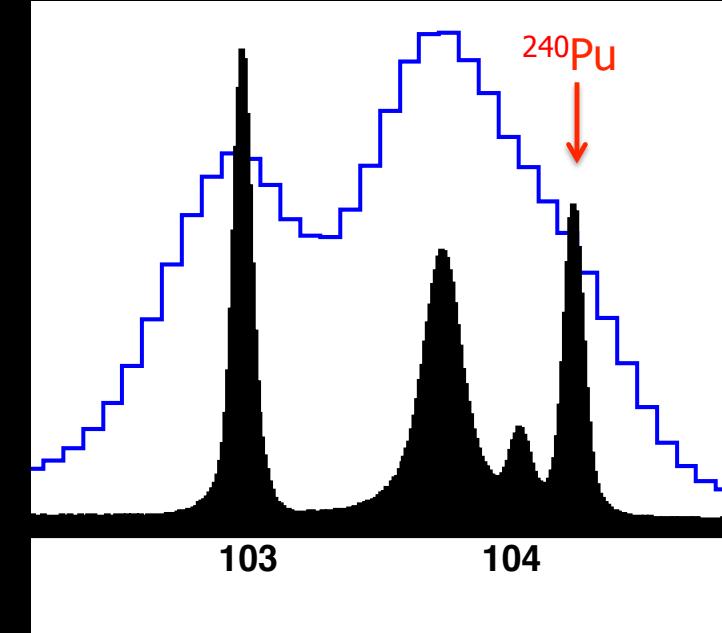
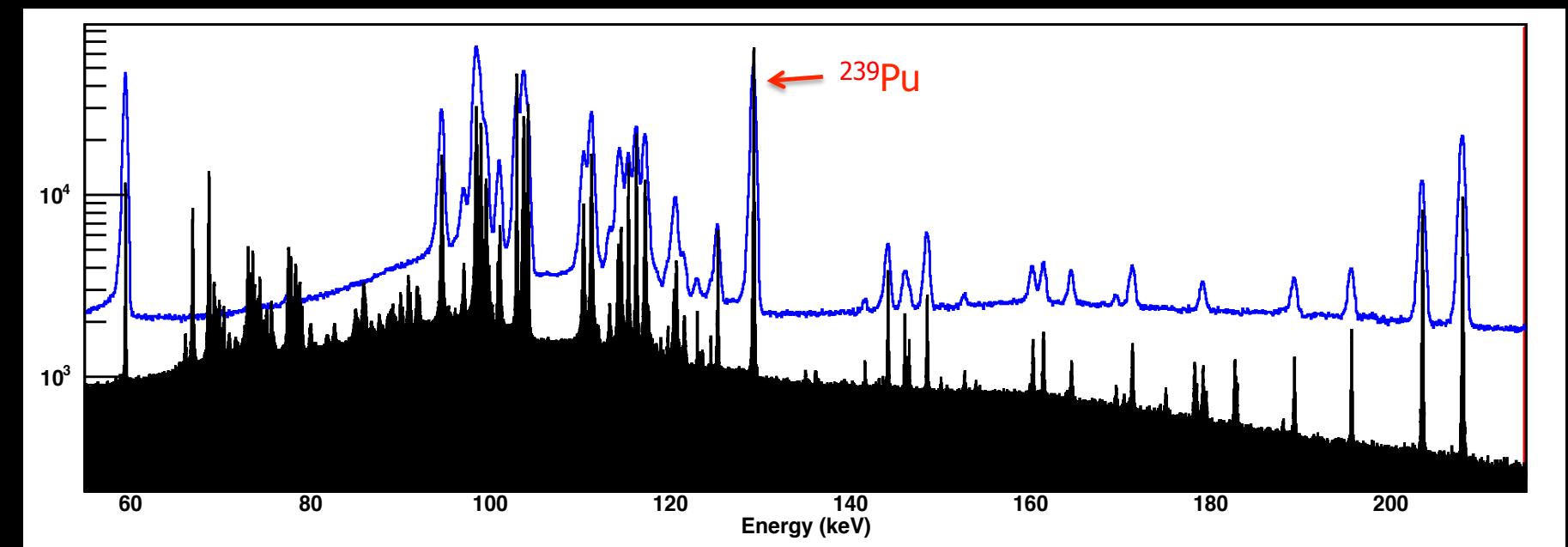


# Energy resolution for X- and $\gamma$ -ray spectroscopy

*Factor of ten better than conventional semiconductor technology*





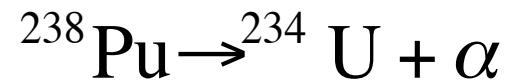
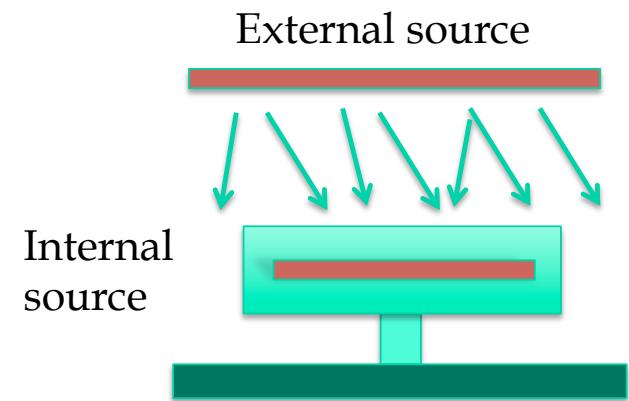
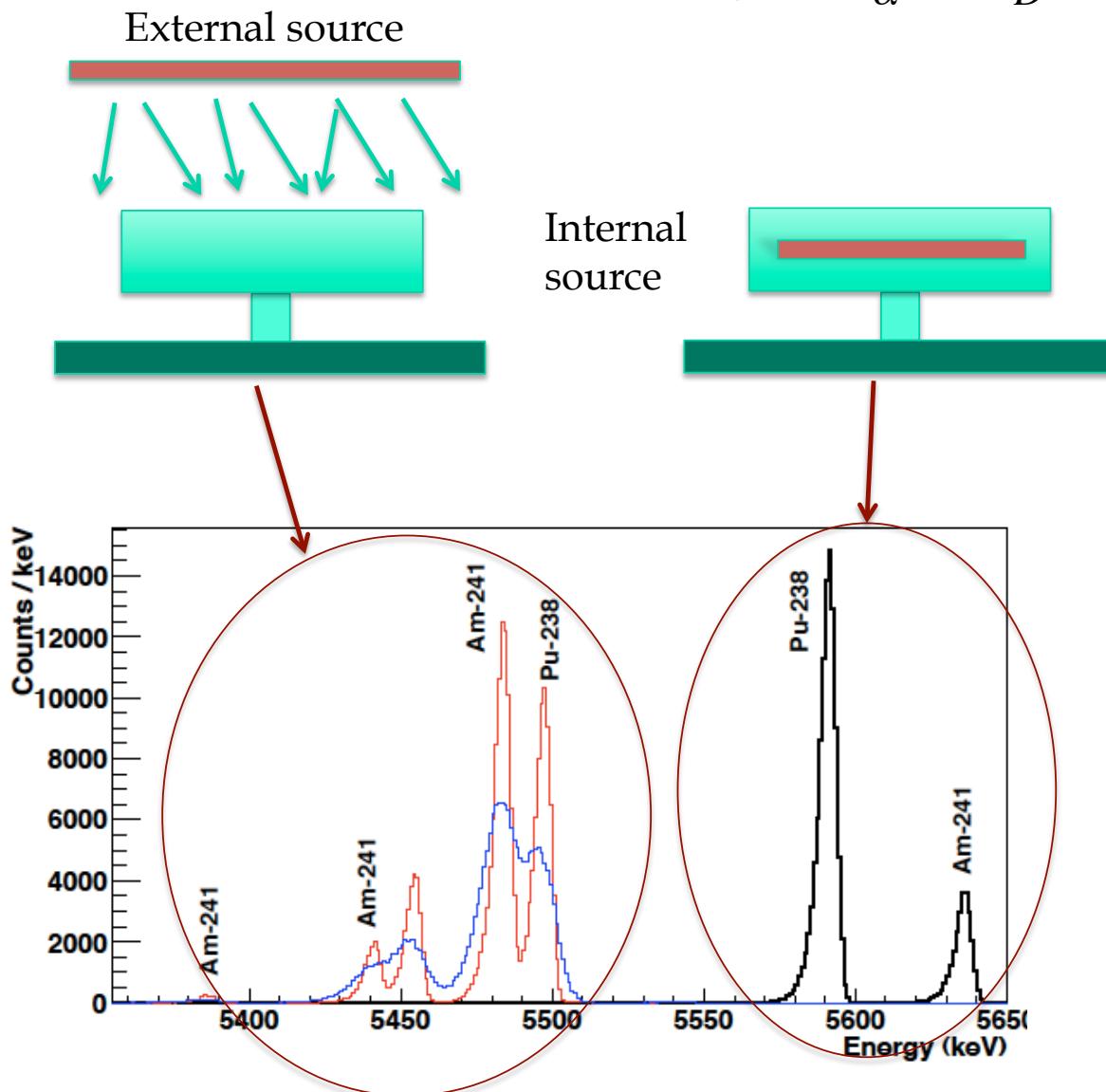


$\sim 50,000,000$  counts  
256-pixel array  
 $\Delta E \sim 70$  eV FWHM

# External vs. internal for $\alpha$ -decaying isotopes

*Decay products are the alpha particle and the daughter atom*

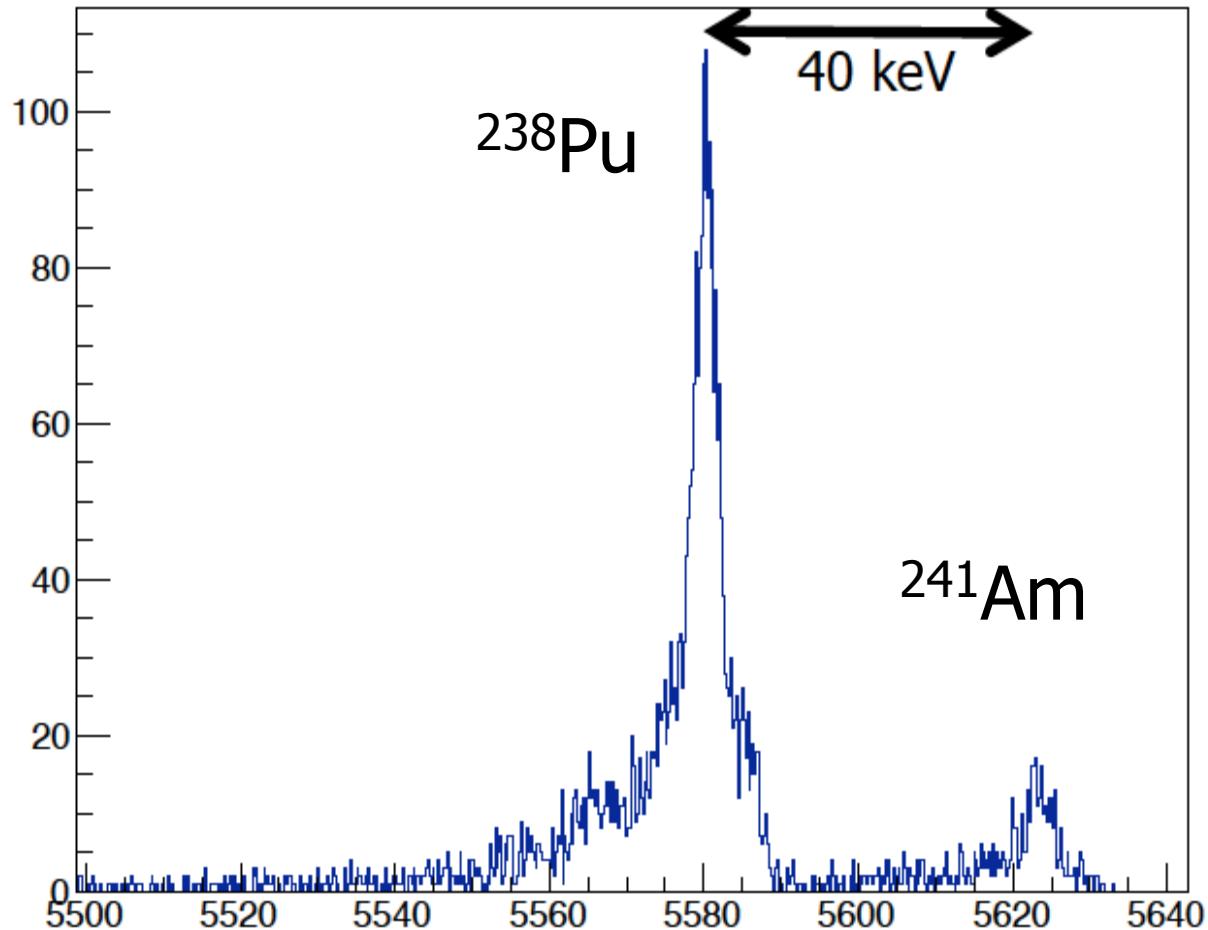
$$Q = E_\alpha + E_D$$



	Energy (keV)	Branch Fraction
Q	5593	1
$\alpha$	5499	0.71
$\alpha$	5456	0.29
$\gamma$	43.5	$1 \times 10^{-4}$
$\gamma$	99.85	$7 \times 10^{-5}$

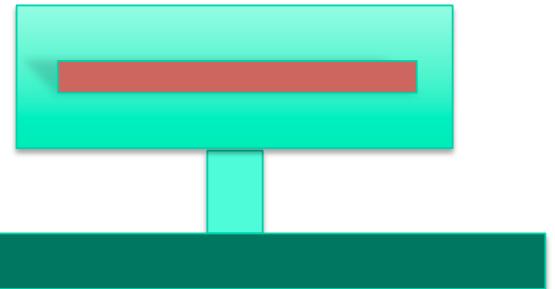
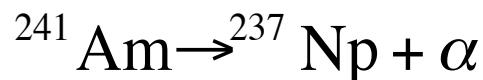
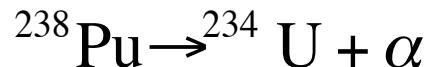
## First high-resolution mixed actinide Q spec

*Shows 3X increase in separation between peak centers*



## Some radioactive decays of interest

$\alpha, \beta, \text{electron capture}$

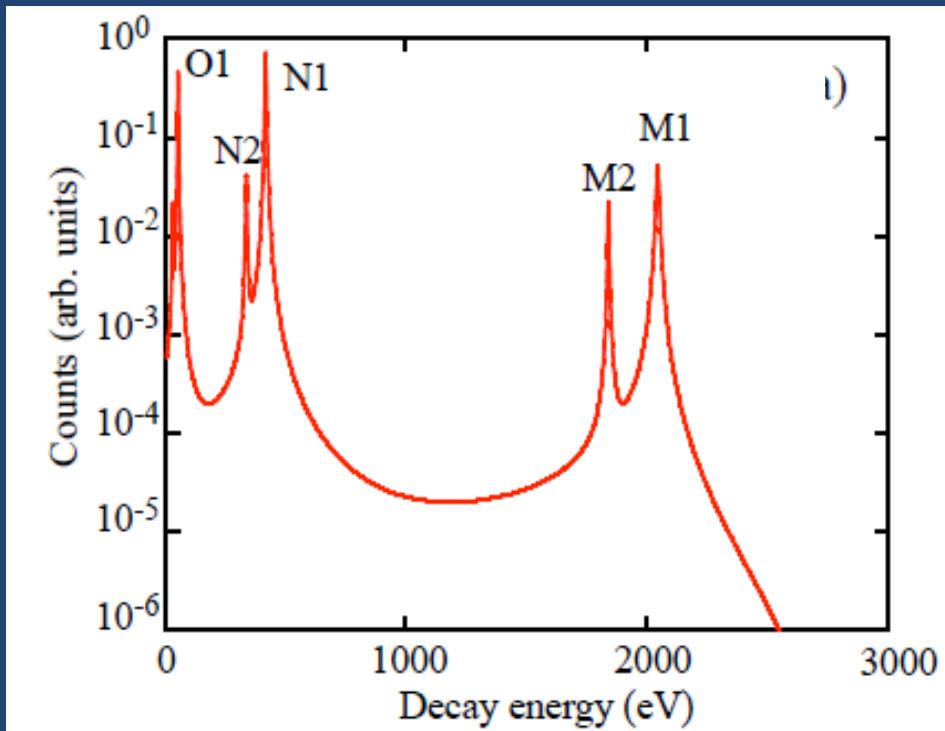


*Key linking science issue*

The chemical form and physical microstructure of the combination of absorber and source affects energy thermalization.



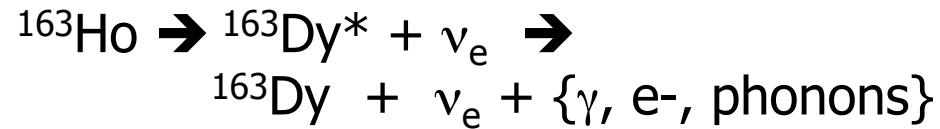
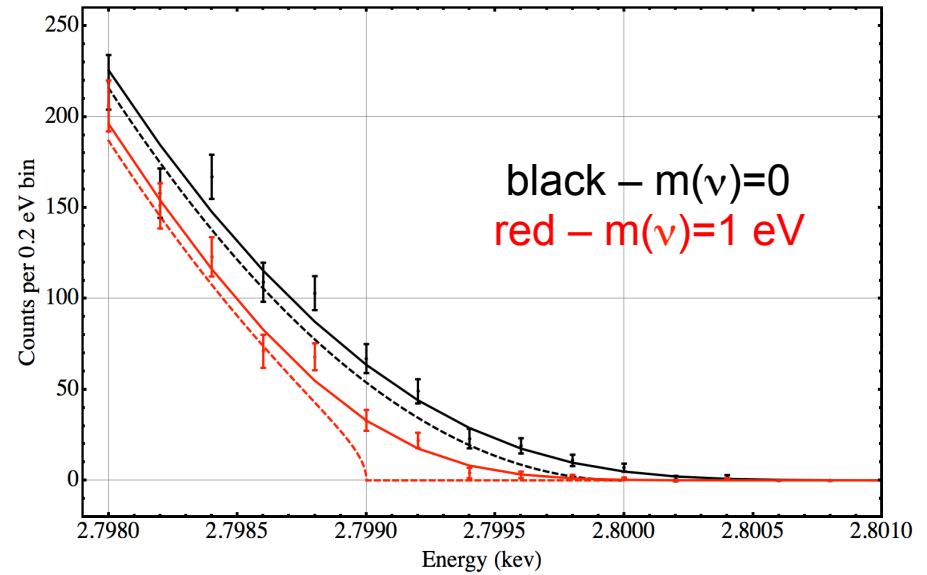
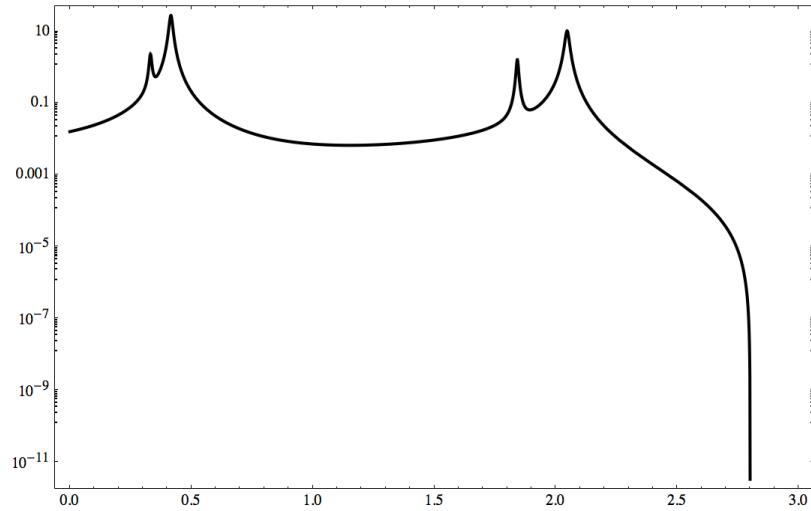
# Electron-capture endpoint with $^{163}\text{Ho}$



$$p(E) = A(Q - E) \sqrt{(Q - E)^2 - m^2} \sum_k \frac{W_h \Gamma_h}{(E - E_k)^2 + (\Gamma_h/2)^2}$$

Original idea: A. De Rújula and M. Lusignoli, PRB, 1982  
also, see: M. Galeazzi et al., arXiv:1202.4763, 2012  
L. Gastaldo et al., arXiv:1206.5647, 2012

# Calorimetric ECS spectroscopy spectral shape



Large microcalorimeter arrays for spectroscopy

+

Embedded radionuclides

+

Isotope production facility

# How do we figure out *absolute* neutrino mass?

## $\beta$ -decay

Model-independent (from kinematics)  
KATRIN, MARE, ... $^{163}\text{Ho}$

## $0\nu\beta\beta$ -decay

Model-dependent (Majorana, CP-phases)  
CUORE, EXO, Majorana, ...

Neutrino mass

## Cosmology

Model-dependent ( $\Lambda$ -CDM +  $m_\nu$  +  $N_{\text{eff}}$ )  
CMB, SN1a, BAO, H0, clusters...

# Simplified neutrino mass equations

$$m_{\text{cosmo}} = \sum_k m_k$$

$$m_{\beta\beta} = \left| \sum_k U_{ek}^2 m_k \right|$$

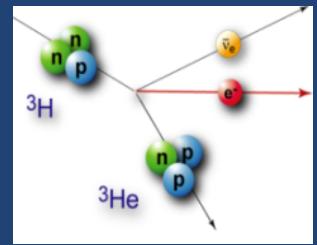
$$m_{\text{kinematic}} = \sum_k |U_{ek}|^2 m_k^2$$

Three complementary methods addressing different aspects of neutrino mass.

Only kinematic techniques like ours are model-independent.

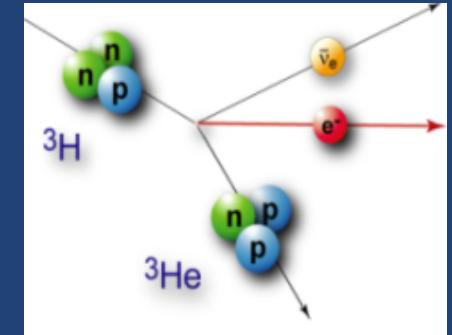
$m_{\beta\beta}$  subject to complex phases.  $m_{\text{kinematic}}$  is not.

# Beta and electron-capture decays to measure $m(\nu_e)$

Reaction		Half-life	$Q$
$^3\text{H}_2 \rightarrow ^3\text{He}^3\text{H}^* + \nu_e^- + e^-$		12.3 yr	18.6 keV
$^{187}\text{Re} \rightarrow ^{187}\text{Os} + \nu_e^- + e^-$		43 Gyr	2.5 keV
$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e^-$ $\rightarrow ^{163}\text{Dy} + \nu_e^- + \{\gamma, e^-, \text{phonons}\}$	4.3 kyr	2.2-2.8 keV	

Measure the maximum  
electron kinetic energy

# KATRIN tritium endpoint experiment, now-2019



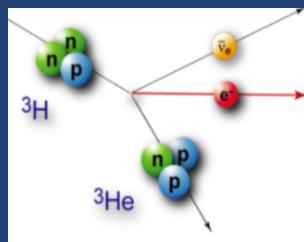
**discovery potential**  
 $m(\nu) = 0.35 \text{ eV} (5\sigma)$

**sensitivity (90% CL)**  
 $m(\nu) < 0.2 \text{ eV}$

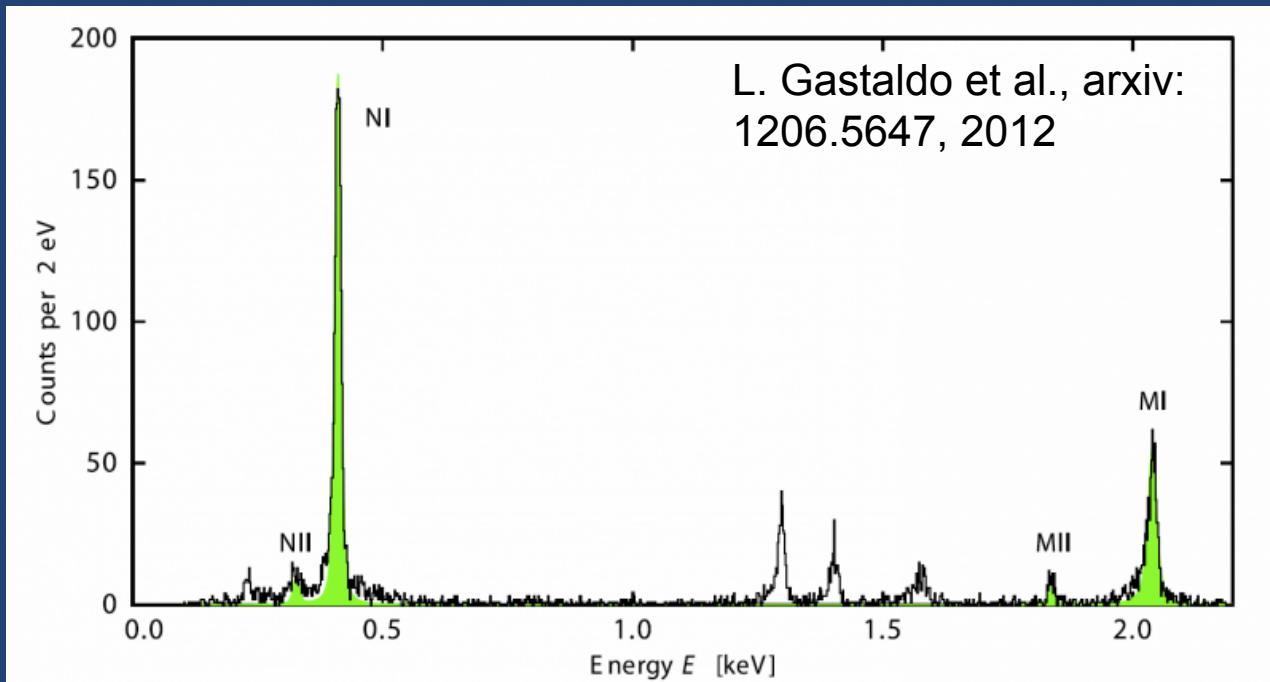
“Looking for Neutrinos, Nature's Ghost Particles,” Smithsonian

# Can Ho-163 set a better mass limit?

Reaction	Half-life	Q
$^3\text{H}_2 \rightarrow ^3\text{He}^3\text{H}^* + \bar{\nu}_e + e^-$	12.3 yr	18.6 keV
$^{187}\text{Re} \rightarrow ^{187}\text{Os} + \bar{\nu}_e + e^-$	43 Gyr	2.5 keV
$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$ $\rightarrow ^{163}\text{Dy} + \nu_e + \{\gamma, e^-, \text{phonons}\}$	4.3 kyr	2.2-2.8 keV
Thermalize and measure this energy		



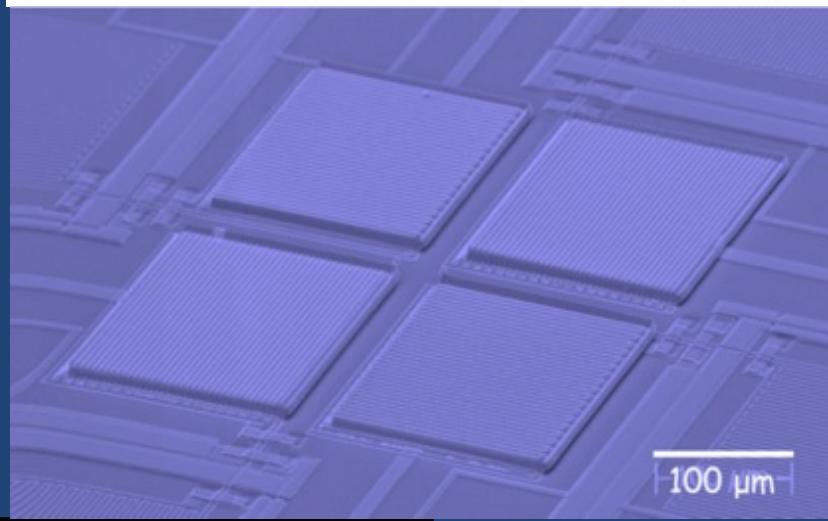
# Proof of principle spectrum from ECHo



Data with magnetic calorimeter single pixel, Au absorber with implanted  $^{163}\text{Ho}$ .

12 eV FWHM energy resolution

ECHo collaboration:  
Electron Capture 163-Holmium experiment



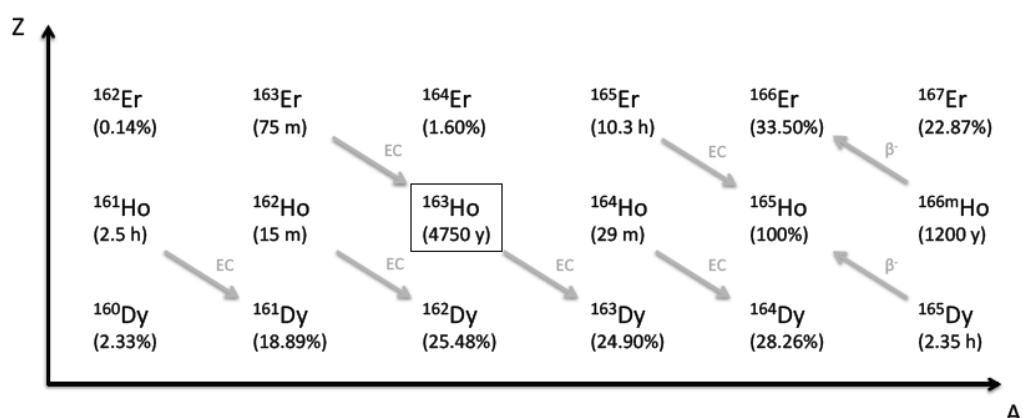
# $^{163}\text{Ho}$ Isotope Production

J. W. Engle et al., NIM B, 311 (2013) 131-138

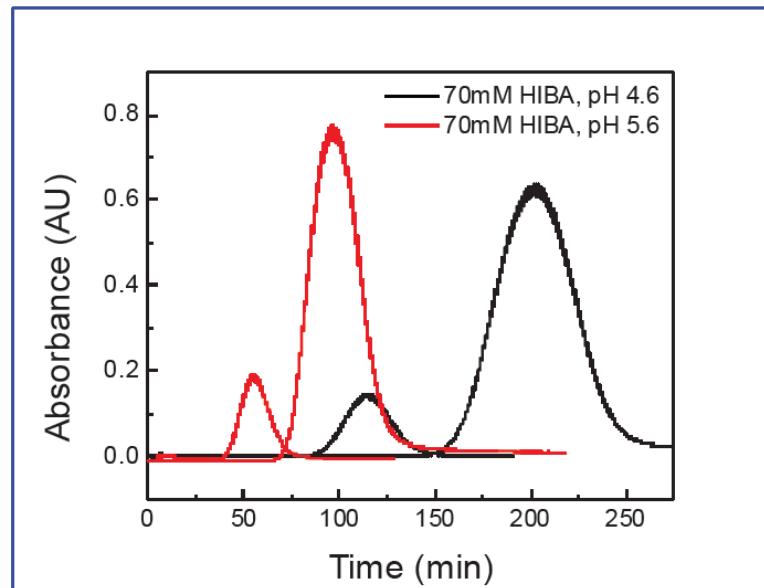
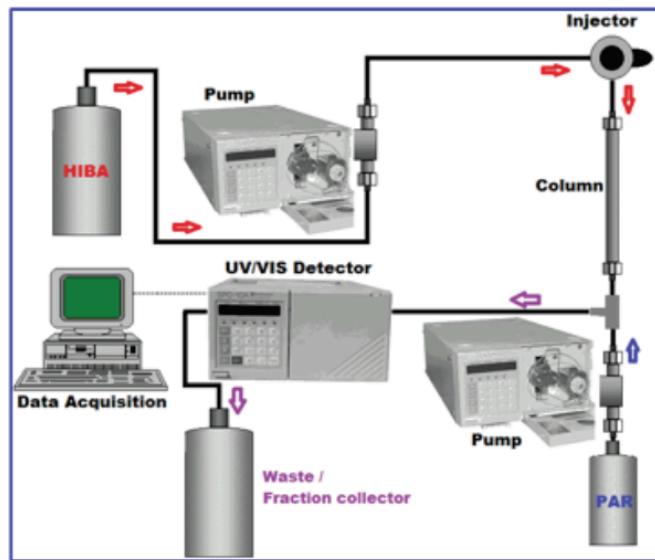
Incident Particle	Target	$^{163}\text{Ho}$ Production Rate (atoms/hr)	$^{166\text{m}}\text{Ho}$ Production Rate (atoms/hr)	$^{163}\text{Ho}/^{166\text{m}}\text{H}$ o Atom Ratio
(a) 16 MeV p <sup>+</sup>	<sup>nat</sup> Dy	$10^{14}$	$10^{4-5}$	$10^{9-10}$
(b) 24 MeV p <sup>+</sup>	<sup>nat</sup> Dy	$10^{15}$	$10^{6-9}$	$10^{6-9}$
(c) 40 MeV $\alpha$	<sup>nat</sup> Dy	$10^{13}$	$10^7$	$10^5$
(c) 40 MeV $\alpha$	<sup>161</sup> Dy	$10^{10}$	$10^3$	$10^7$
(d) $10^{14}$ neutrons/cm <sup>2</sup> /sec	<sup>162</sup> Er	$10^{13-15}$ (per mg <sup>162</sup> Er)	$10^{10-12}$	$10^{3-5}$

Proton irradiation of Dy or neutron irradiations of Er

Greater radio-isotopic purity is achievable using charged particle irradiations



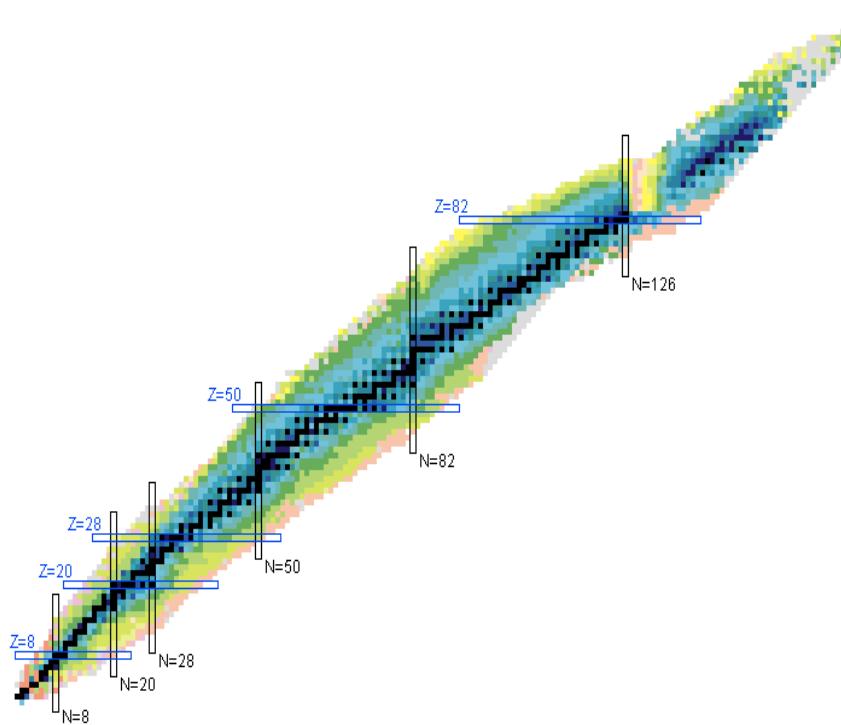
# Chemical separation



- Chemical separation to isolate  $^{163}\text{Ho}$  from irradiated dysprosium target
- High performance liquid chromatography (HPLC)
  - Cation exchange resin
  - $\alpha$ -HIBA as eluent
  - UV-Vis detection
  - Post column detection reagent 4-(2-pyridylazo)resorcinol

# Some possible surrogate isotopes

*Use for prototyping methods for isotope encapsulation and sensor designs*



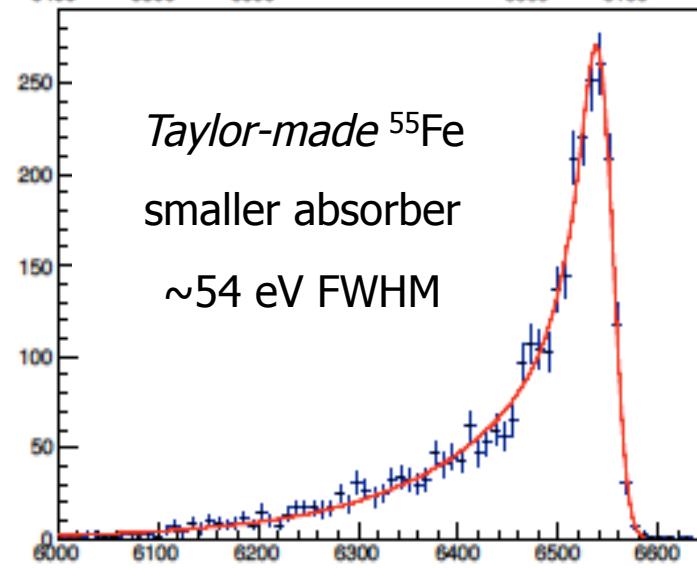
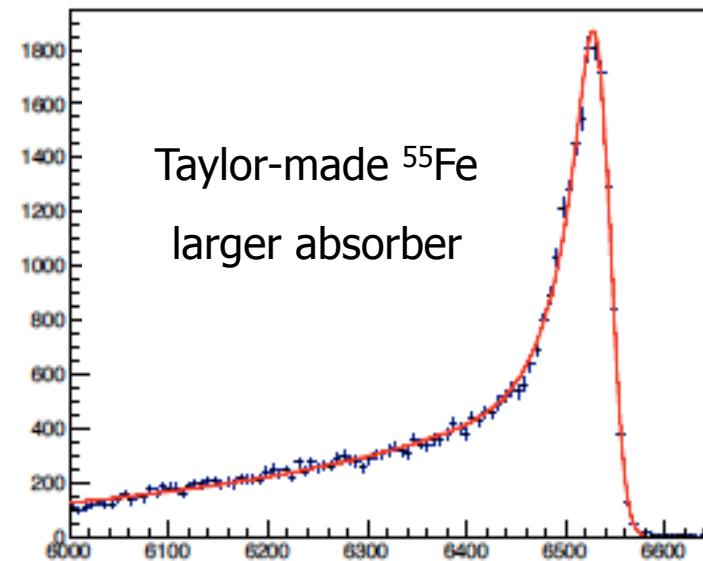
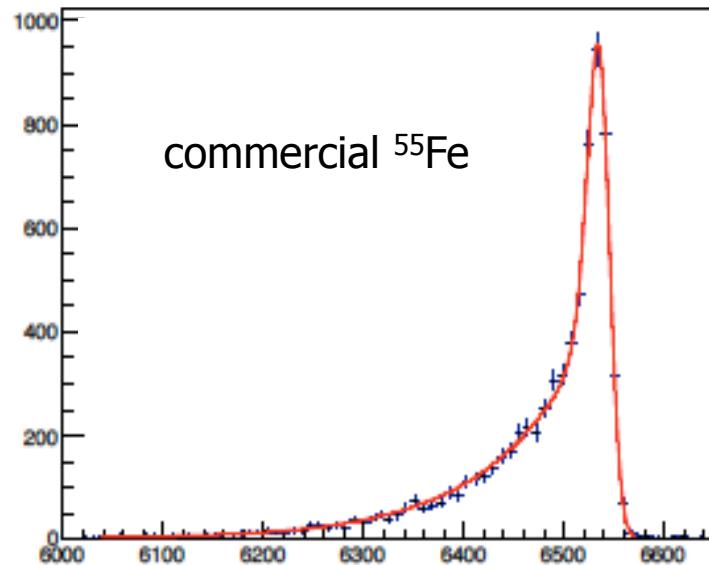
Parent			Gamma rays?	Q (keV)	Child	
isotope	half life	units			isotope	stable?
7Be	53.28	day	y	862	7Li	y
37Ar	35	day	n	813	37Cl	y
41Ca	1.00E+05	year	n	421	41K	y
44Ti	52	year	y	268	44Sc	n
49V	337	day	n	602	49Ti	y
51Cr	27.7	day	y	751	51V	y
53Mn	3.70E+06	year	n	596	53Cr	y
54Mn	312	day	y	1377	54Cr	y
55Fe	2.73	year	n	231	55Mn	y
57Co	271.8	day	y	836	57Fe	y
56Ni	6	day	y	2140	56Co	n
67Ga	3.2	day	y	1001	67Zn	y
68Ge	270.8	day	n	110	68Ga	n
71Ge	11.4	day	n	233	71Ga	y*
73As	80.3	day	y	340	73Ge	y
72Se	8.5	day	y	330	72As	n

Isotopes that decay solely by electron capture to the nuclear ground state of a very long lived or stable product (child) isotope.

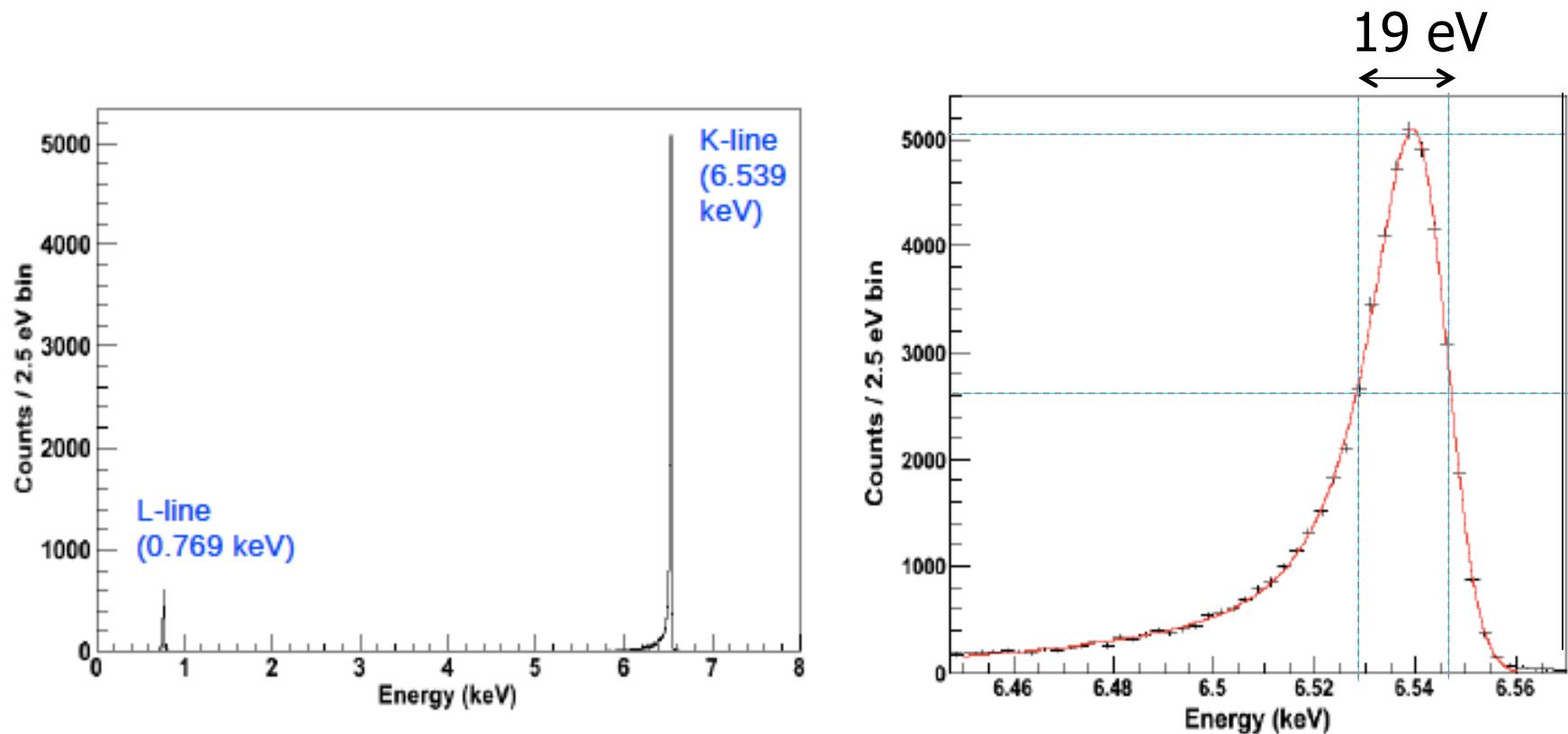
High Q is OK for prototyping.

Screening is incomplete and not yet detailed enough.

## Spectral results ECS of $^{55}\text{Fe}$



# Improved spectral results ECS of $^{55}\text{Fe}$



$$\sigma = 5.25 \text{ eV}$$

$$2.35 \sigma = 12.4 \text{ eV}$$

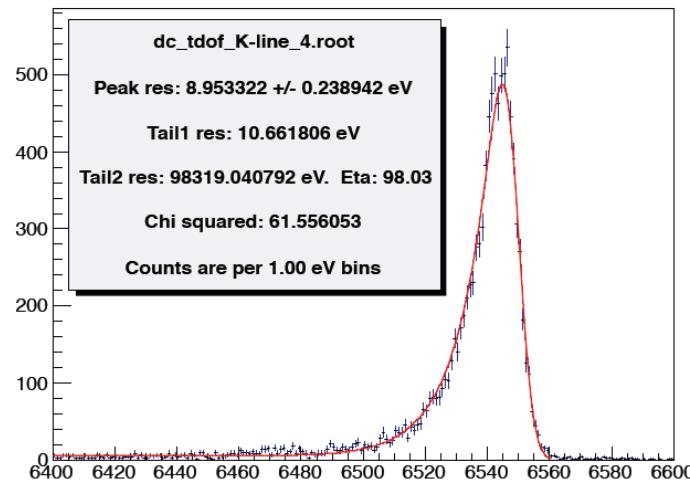
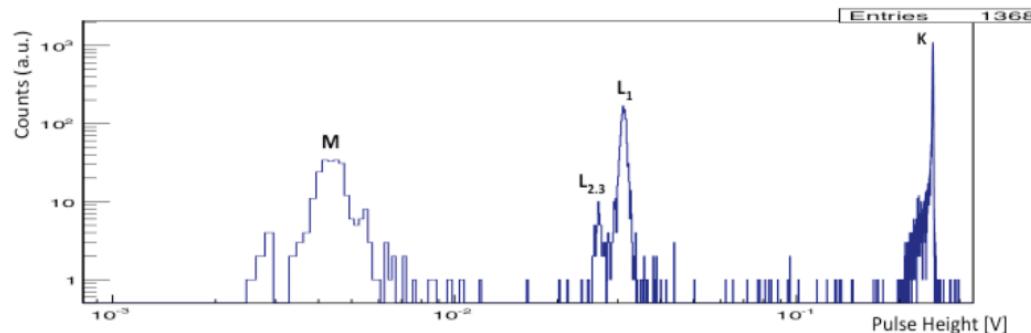
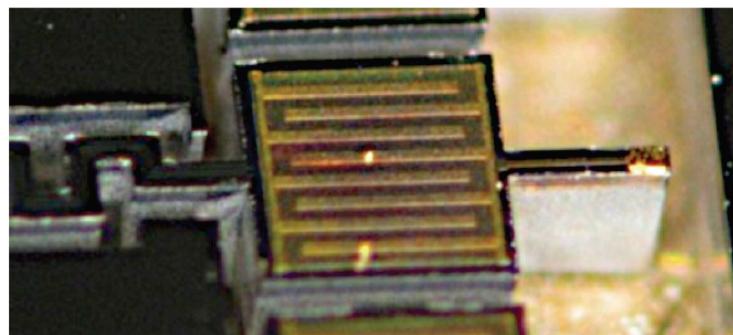
$$\lambda_1 = 8.9 \text{ eV}$$

$$\lambda_2 = 47 \text{ eV}$$

$$\eta = 0.37$$

# Electron Capture Spectroscopy of embedded $^{55}\text{Fe}$

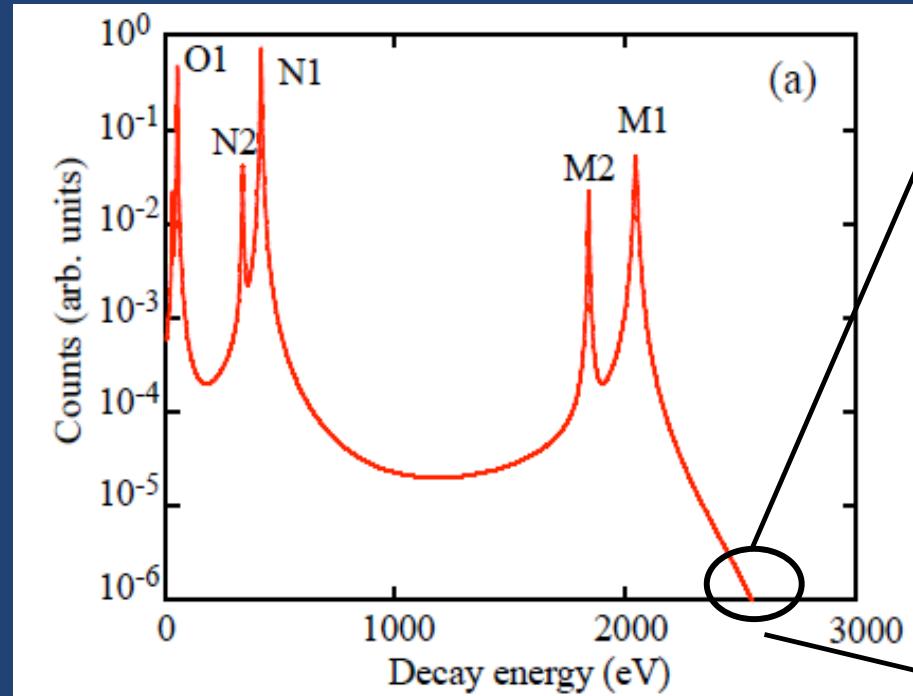
- Electroplated  $^{55}\text{Fe}$  in diffusion bonded Au
- Absorber C  $\sim 0.17 \text{ pJ/K}$   
33x45x18  $\mu\text{m}$ , diffusior bonded to TES structure
- Total C  $\sim 1 \text{ pJ/K}$
- 9.0+0.2 eV Resolution



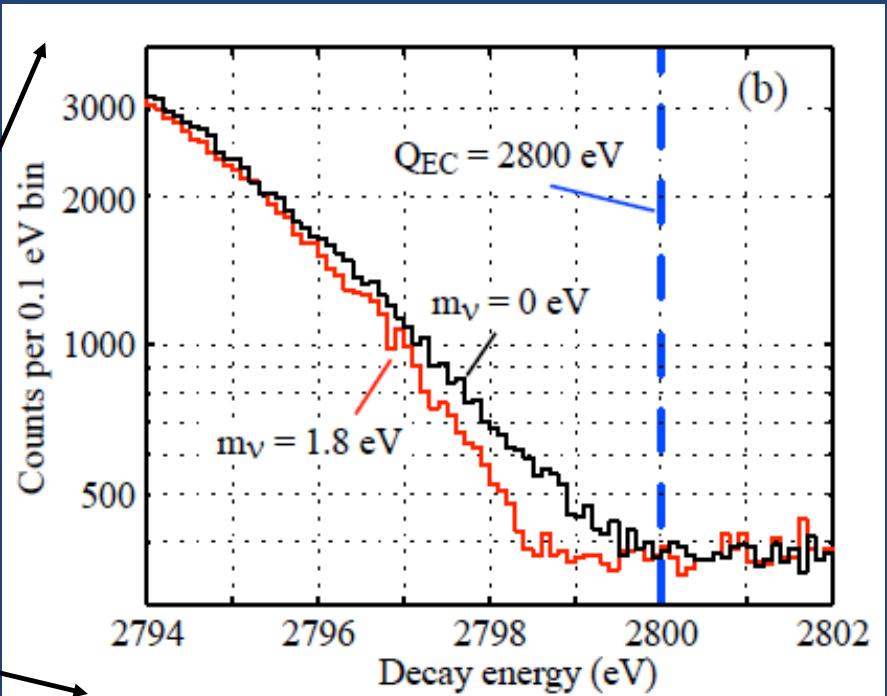
# $^{163}\text{Ho}$ decay spectrum gives neutrino mass

- Directly measure  $\nu$  mass from endpoint energy of electron-capture decay of  $^{163}\text{Ho}$
- Thermalize and measure decay energy =  $Q - E_\nu$        $E_\nu = \text{kinetic energy} + m_\nu c^2$

Calculated  $^{163}\text{Ho}$  decay spectrum

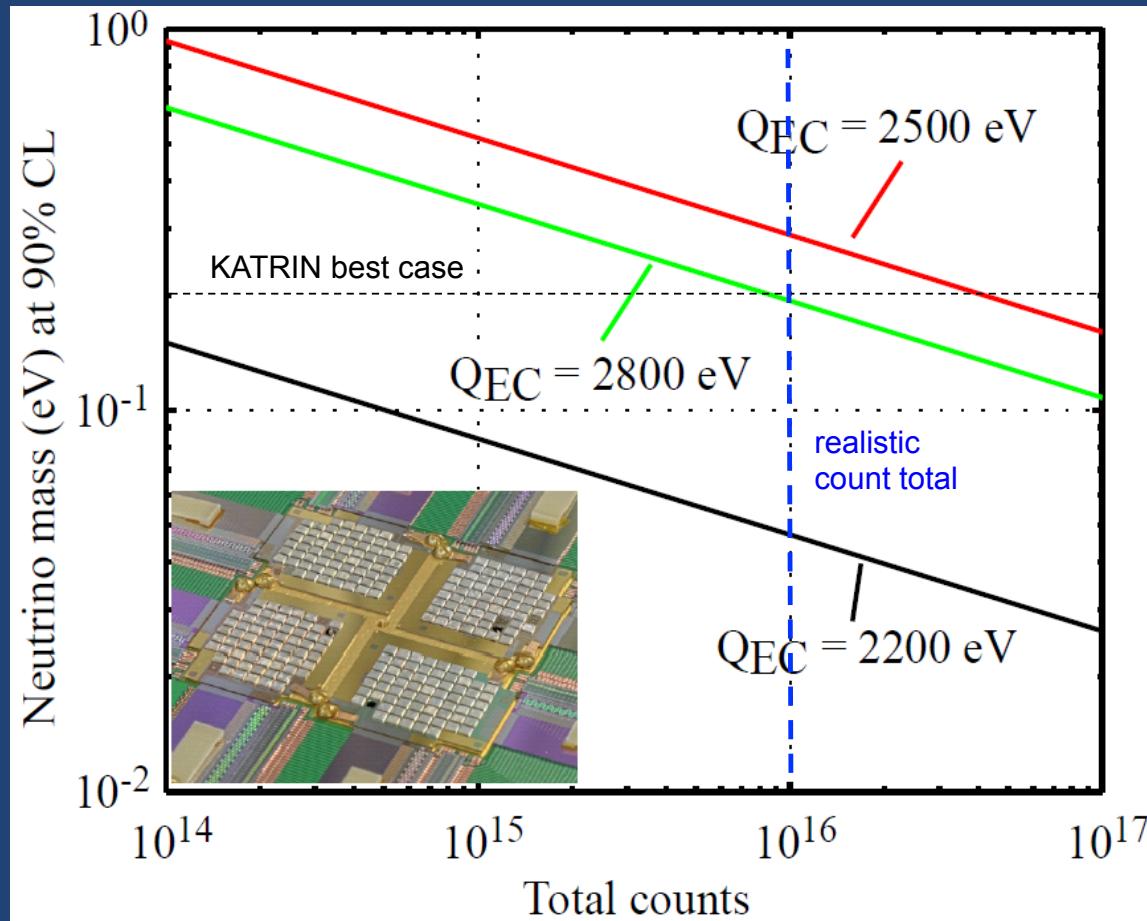


Zoom on endpoint



- “Missing” energy at endpoint is  $m_\nu c^2$
- Need very precise energy sensors

# Many decays needed for useful mass limits

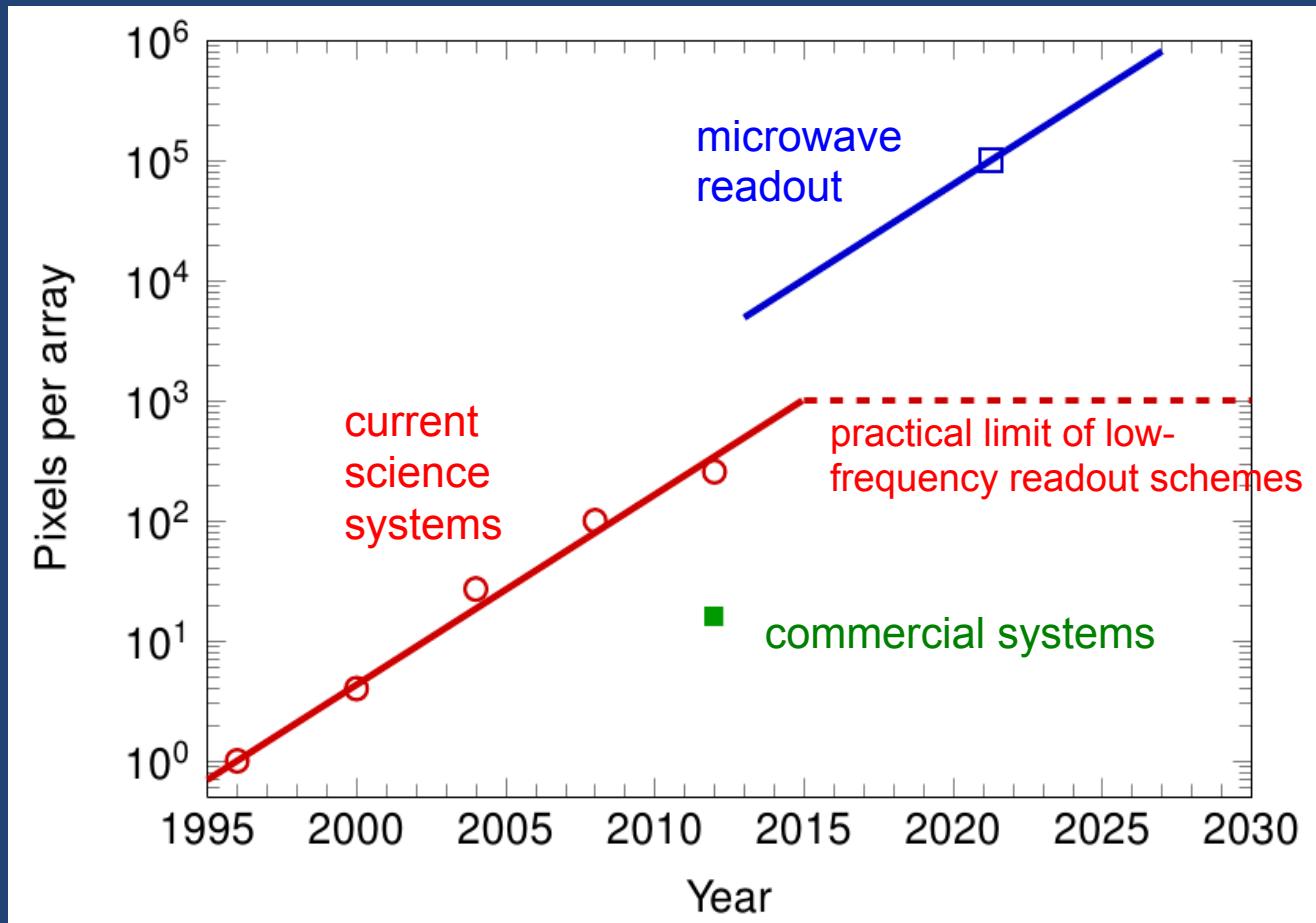


realistic  
3 × 10<sup>5</sup> pixels at  
200 cps/pixel  
for 5 years =  
10<sup>16</sup> counts

- A huge scale-up in array size is needed: from 256 pixels (shown) to  $\sim 10^5$
- Science reach dependent on Q and statistics
- Mass limit can be better than best KATRIN predictions. Systematics different, simpler.

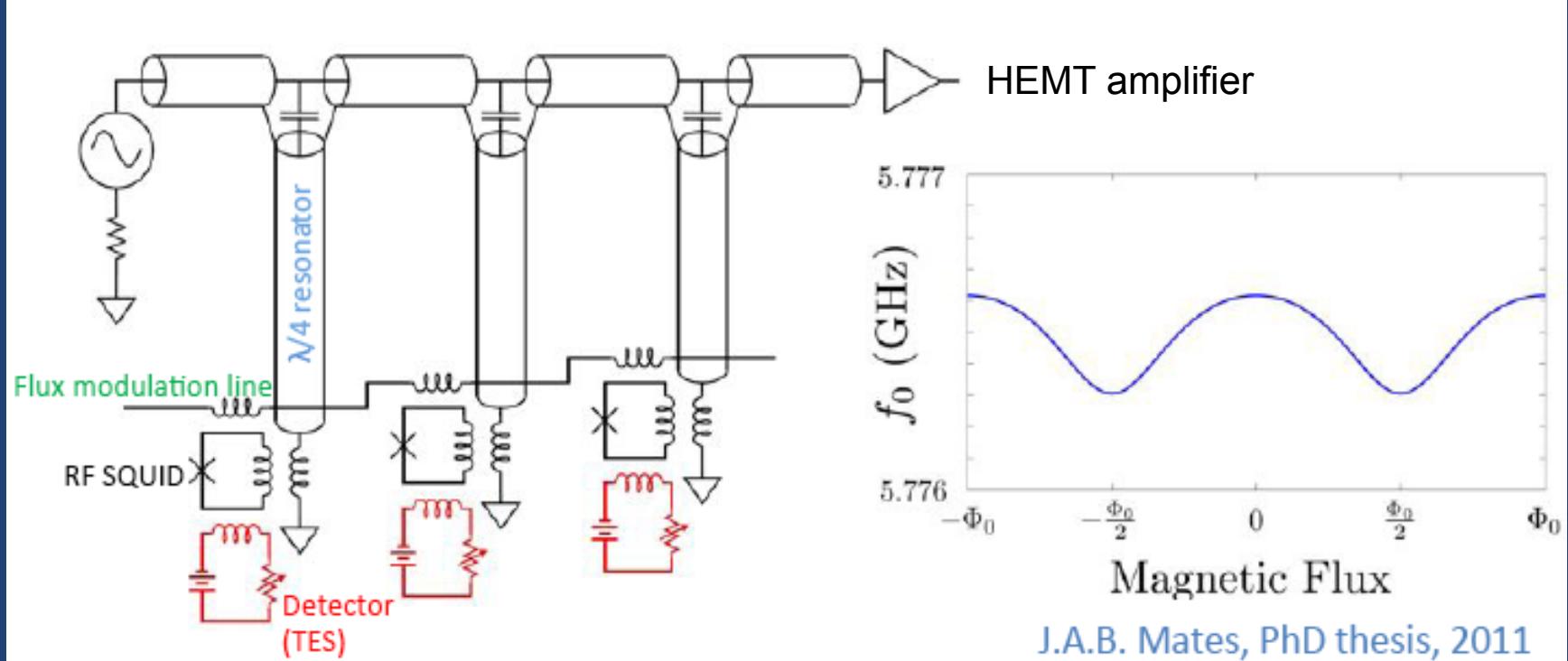
# Growth of calorimetric sensor arrays

- We are proposing a paradigm shift in the size of calorimetric sensor arrays



- Microwave readout will shift growth curve
- Microwave readout will enable neutrino mass measurement

# Microwave SQUID multiplexing



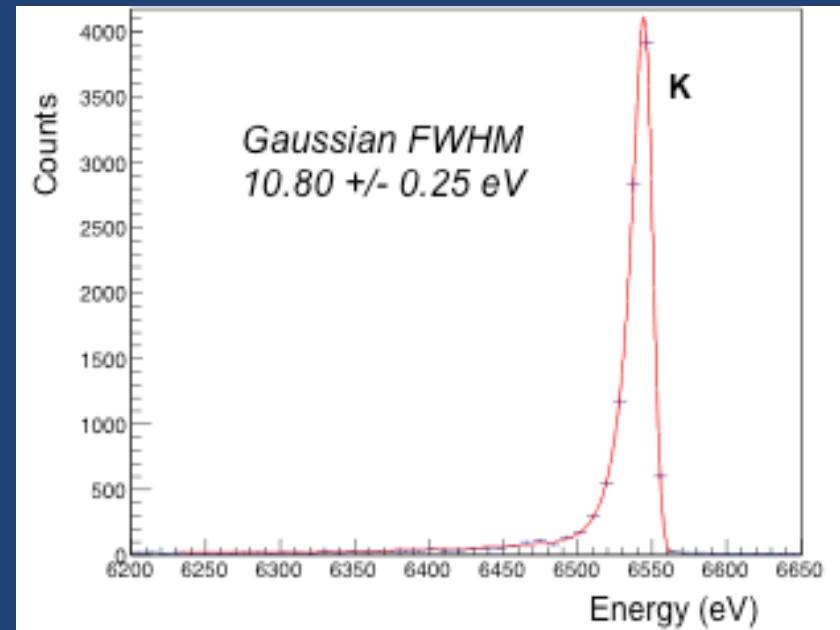
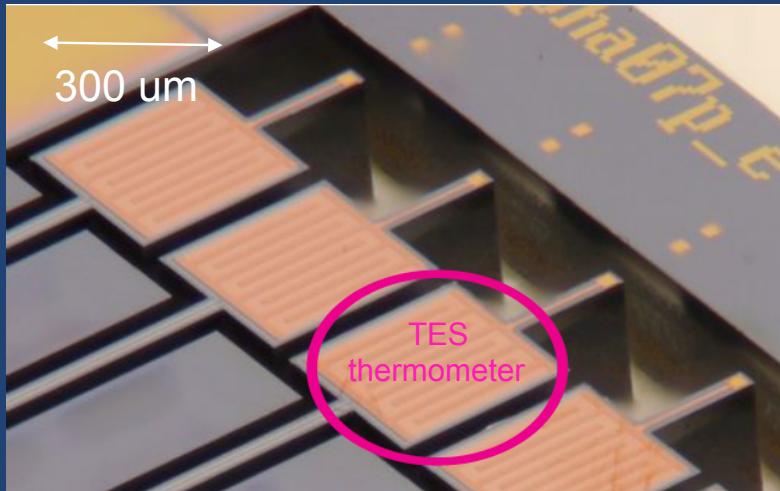
1 HEMT provides  $\sim 10$  GHz of bandwidth!

10 GHz / 1-10 MHz per sensor  $10^3 - 10^4$  sensors per amplifier

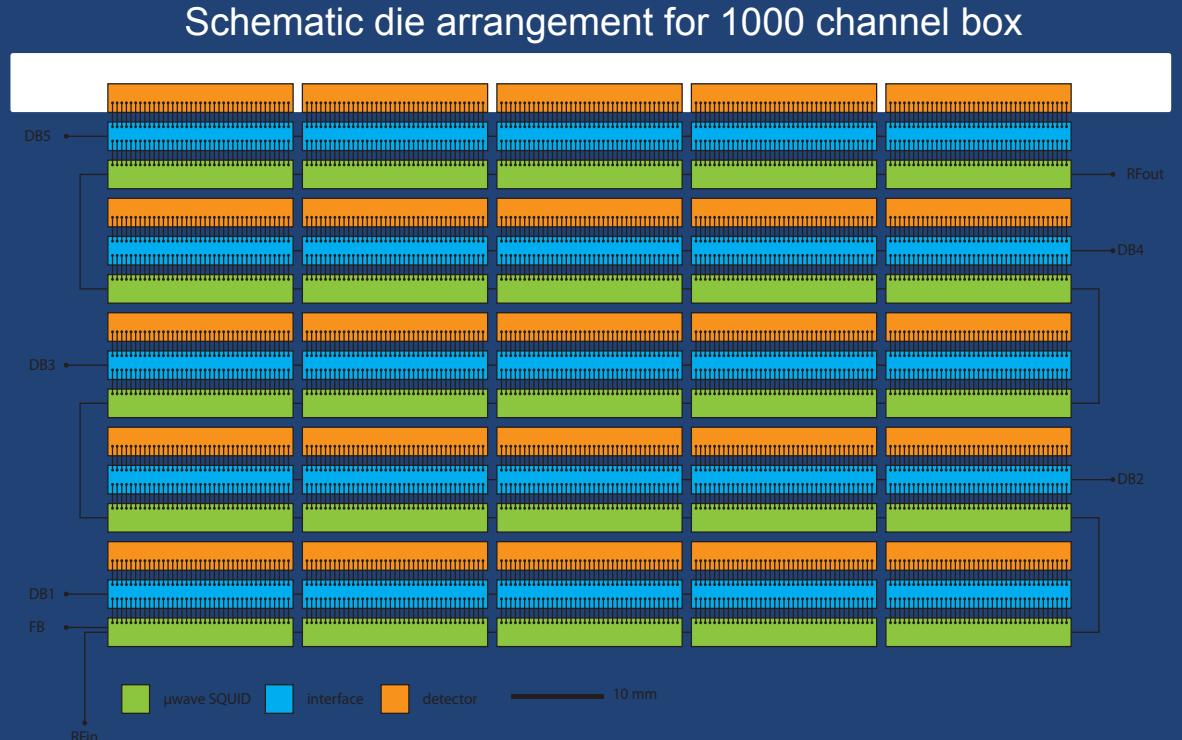
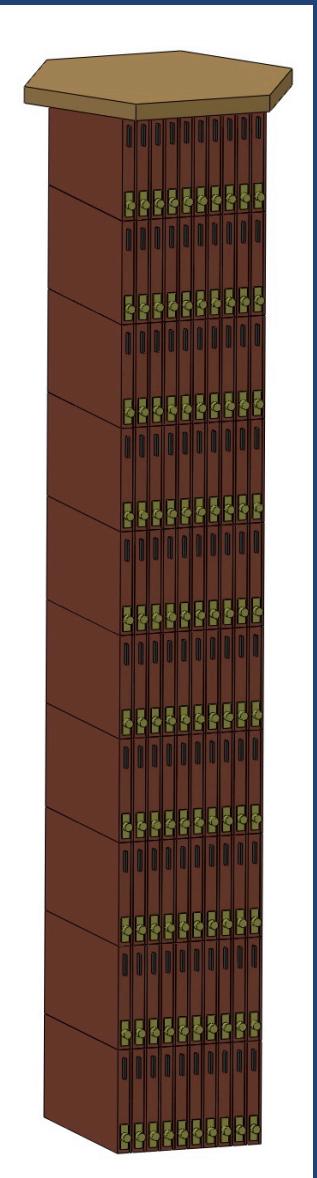
Flux ramp modulation eliminates need for flux-locked loop

The major challenge is synthesizing and demodulating the carrier tones

# New sensor design under test now ...



# What will $10^5$ pixels look like?



1000 channel subcell

$10^5$  pixels  
volume: 12.7 cm by 63.5 cm by 9.5 cm  
mass: ~20 kg  
200 coaxial cables, 600 dc wires  
static heat load at 100 mK: < 20  $\mu$ W  
25 HEMT amplifiers (4-8 GHz)  
70-100 processed wafers

X    $\gamma$     $\alpha$    Q    $\beta$    e<sup>-</sup>

$E_C$

X     $\gamma$      $\alpha$     Q     $\beta$      $e^-$

*Calorimetric electron capture energy spectroscopy  
combines many of these.*